Progenitors of Type Ia Supernovae: Circumstellar Interaction, Rotation, and Steady Hydrogen Burning

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Abstract.

Among the important issues in identifying the progenitor system of Type Ia supernovae (SNe Ia), we focus mostly on circumstellar interaction in SN 2002ic, and give brief discussion on the controversial issues of the effects of rotation in merging double degenerates and steady hydrogen shell burning in accreting white dwarfs.

SN 2002ic is a unique supernova which shows the typical spectral features of SNe Ia near maximum light, but also apparent hydrogen features that have been absent in SNe Ia. Based on the hydrodynamical models of circumstellar interaction in SN Ia, we suggest that circumstellar medium is aspherical (or highly clumpy) and contains $\sim 1.3 M_\odot$. Possible progenitor systems of SN 2002ic are discussed.

1. Introduction

Type Ia supernovae (SNe Ia) are characterized by the lack of hydrogen and the prominent Si line in their spectra near maximum light and widely believed to be thermonuclear explosions of mass-accreting white dwarfs in binary systems. SNe Ia have been used as a "standard candle" to determine cosmological parameters thanks to their relatively uniform light curves and spectral evolution. SNe Ia are also the major sources of Fe in the galactic and cosmic chemical evolution. Despite such importance, the immediate progenitor binary systems have not been clearly identified yet (e.g., Nomoto et al. 2000; Livio 2000).

Recent progress in identifying the progenitor systems includes the study of circumstellar interaction suggested from high velocity materials (e.g., Thomas et al. 2004; Gerardy et al. 2004; Mazzali et al. 2004), especially for SN 2002ic, which has been changed from Type Ia to Type IIn supernova (Hamuy et al. 2003). We describe hydrodynamical models to infer the nature of circumstellar matter and thus the progenitor (§2-5).

The issue of "*single degenerate vs. double degenerates*" has long been controversial. For this we discuss the effects of rotation in the double degenerate scenario (§6), and steady hydrogen shell burning in the single degenerate scenario (§7).

2.   Circumstellar Medium of Type Ia Supernovae

For a model of SN Ia progenitors, Hachisu et al. (1999ab) proposed a single degenerate model in which the white dwarf blows a massive and fast wind (up to $10^{-4} M_\odot$ yr^{-1} and 2000 km s^{-1}) and avoids a formation of common envelope when the mass transfer rate from the normal companion exceeds a critical rate of $\sim 1 \times 10^{-6}\ M_\odot$ yr^{-1} (Nomoto 1982). Such an evolutionary phase is dubbed "accretion wind evolution" instead of "common envelope evolution." Such a binary can keep its separation almost unchanged. The white dwarf can steadily accrete a part of the transferred matter and eventually reach the Chandrasekhar mass.

In the strong wind model, the WD winds form a circumstellar envelope around the binary systems prior to the explosion. When the ejecta collide with the circumstellar envelope, X-rays, radio, and Hα lines are expected to be emitted by shock heating. Attempts have been made to detect such emissions, but so far no signature of circumstellar matter has been detected.

The upper limit set by X-ray observations of SN 1992A is $\dot{M}/v_{10} = (2-3) \times 10^{-6} M_\odot$ yr^{-1} (Schlegel, Finkbeiner, & Davis 1998). Radio observations of SN 1986G have provided the most stringent upper limit to the circumstellar density as $\dot{M}/v_{10} = 1 \times 10^{-7} M_\odot$ yr^{-1}, where v_{10} means $v_{10} = v/10$ km s^{-1} (Eck et al. 1995). This is still $10-100$ times higher than the density predicted for the white dwarf winds, because the WD wind velocity is as fast as ~ 1000 km s^{-1}.

For Hα emissions, the upper limit of $\dot{M}/v_{10} = 9 \times 10^{-6} M_\odot$ yr^{-1} has recently been obtained for SN 2000cx using the ESO/VLT (Lundqvist et al. 2003).

3.   SN 2002ic

SN 2002ic was discovered on 2002 November 13 UT at magnitude 18.5 by the Nearby Supernova Factory search (Wood-Vasey et al. 2002). Hamuy et al. (2003) reported strong Fe III features and a Si II λ6355 line in the early-time spectra of SN 2002ic and classified it as a SN Ia.

However, strong Hα emission was also observed. The emission was broad (FWHM > 1000 km s^{-1}) suggesting that it was intrinsic not to an H II region of the host galaxy but to the supernova (SN). The detection of Hα is unprecedented in a SN Ia (e.g., Branch et al. 1995; Livio 2000).

Hamuy et al. (2003) suggested that it arose from the interaction between the SN ejecta and a dense, H-rich circumstellar medium (CSM), as in Type IIn SNe (SNe IIn). If this interpretation is correct, SN 2002ic may be the first SN Ia to show direct evidence of the circumstellar (CS) gas ejected by the progenitor system, presenting us with a unique opportunity to explore the CSM around a SN Ia and the nature of the progenitor system.

3.1.   Spectroscopic Features of SN 2002ic

The spectrum of SN 2002ic is strikingly similar to those of Type IIn SNe 1997cy (Turatto et al. 1998) and 1999E (Rigon et al. 2003). as shown in Figure1. In particular complex line profiles evolve with time, easily detectable in the prominent Hα line. Hα shows at least three components: an unresolved emission
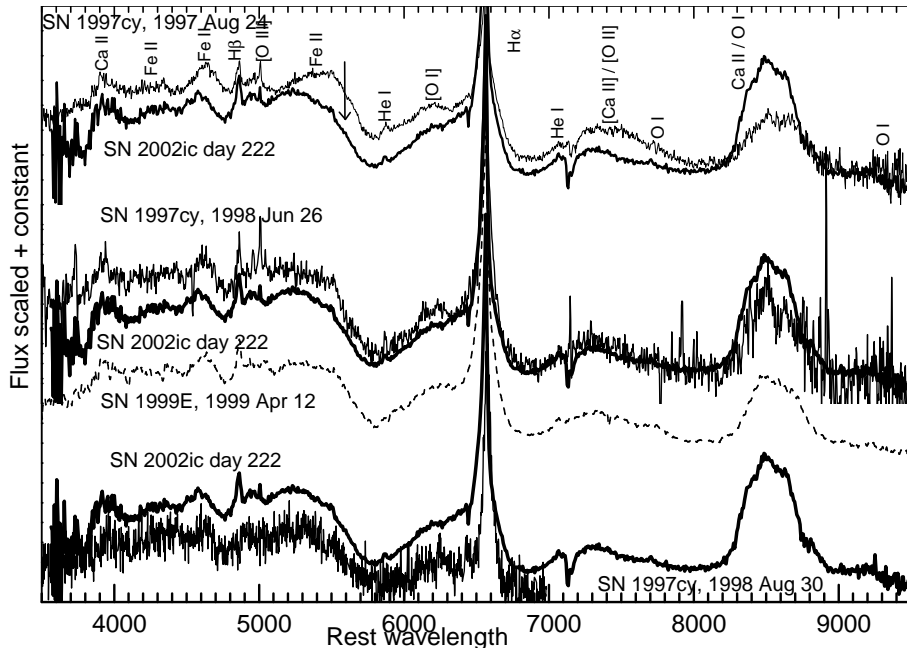
Figure 1. Spectral comparison between SNe 2002ic (thick lines; Subaru, ~ 222 d), 1997cy (thin lines) and 1999E (dashed line).

on the top of broader components, which become narrower with time. At the epoch of the first observation the broadest component has FWHM = 12800 km s^{-1}, and its flux dominates over the intermediate (FWHM = 4300 km s^{-1}) one. One year after the explosion, the broadest component has almost disappeared and the intermediate component (which now has FWHM = 2000 km s^{-1}) is the most evident spectral feature in the spectrum.

SNe 1997cy and 1999E were initially classified as Type IIn because they showed Hα emission. SN 2002ic would also have been so classified, had it not been discovered at an early epoch. SN 1997cy ($z = 0.063$) is among the most luminous SNe discovered so far ($M_V < -20.1$ about maximum light), and SN 1999E is also bright ($M_V < -19.5$). Both SNe 1997cy and 1999E have been suspected to be spatially and temporally related to a GRB (Germany et al. 2000; Rigon et al. 2003). However, both the classification and the associations with a GRB must now be seen as highly questionable in view of the fact that their replica, SN 2002ic, appears to have been a genuine SN Ia at an earlier phase.

3.2. Observed Light Curve of SN 2002ic

The *UVOIR* bolometric light curve of SN 2002ic has been constructed by Deng et al. (2004) from the available BVRI photometry and the spectrophotometry (Hamuy et al. 2003; Wang et al. 2004) as shown in Figure 2. To construct the light curve of SN 2002ic, the Subaru spectrum was integrated. This yielded $L = (5.9 \pm 0.6) \times 10^{42}$ ergs s^{-1}, corresponding to $M_{bol} \sim -18.2$, assuming a distance of 307 Mpc ($H_0 = 65$ km s^{-1} Mpc^{-1}).
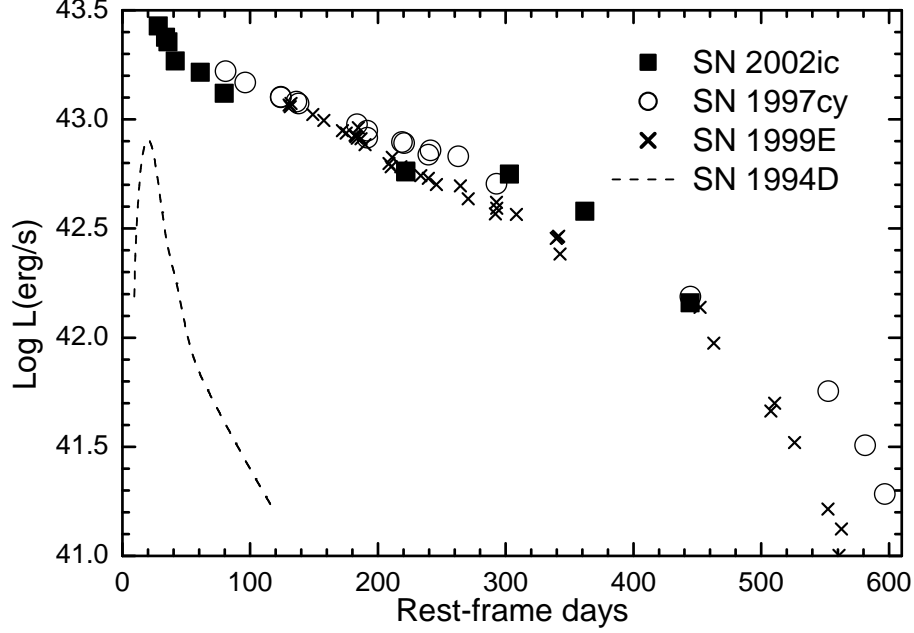
Figure 2.   Comparison of the $UBVRI$ bolometric light curves of SN 2002ic (solid squares) with those of SNe 1997cy (open circles) and 1999E (crosses), and the normal SN Ia 1994D (Contardo et al. 2000; dashed line).

The light curve of SN 2002ic is brighter at maximum and declines much more slowly than typical SNe Ia (Hamuy et al. 2003). The late time light curve of most SNe is powered by the radioactive decay of ^{56}Co to ^{56}Fe. The decline of SN 2002ic is even slower than the Co decay rate, which indicates the presence of another source of energy.

In fact the overall light curve of SN 2002ic resembles Type IIn SN 1997cy (Turatto et al. 1998), suggesting circumstellar interaction for the energy source. Assuming $A_V = 0.00$ for the galactic extinction (NED) SN 2002ic is a factor of 1.3 dimmer than SN 1997cy. We use $UBVRI$ bolometric light curves of SNe 1997cy and 1999E for comparison (Turatto et al. 1998; Rigon et al. 2003) (with a phase computed from their assumed GRB counterparts, which cannot be greatly in error even if, as seems likely, the GRB associations are incorrect). The $UBVRI$ bolometric light curves of the three SNe are also very similar (see Figure2).

4.   Circumstellar Interaction Models

We calculated the interaction between the expanding ejecta and CSM. For the supernova ejecta, we used the the carbon deflagration model W7 (Nomoto,
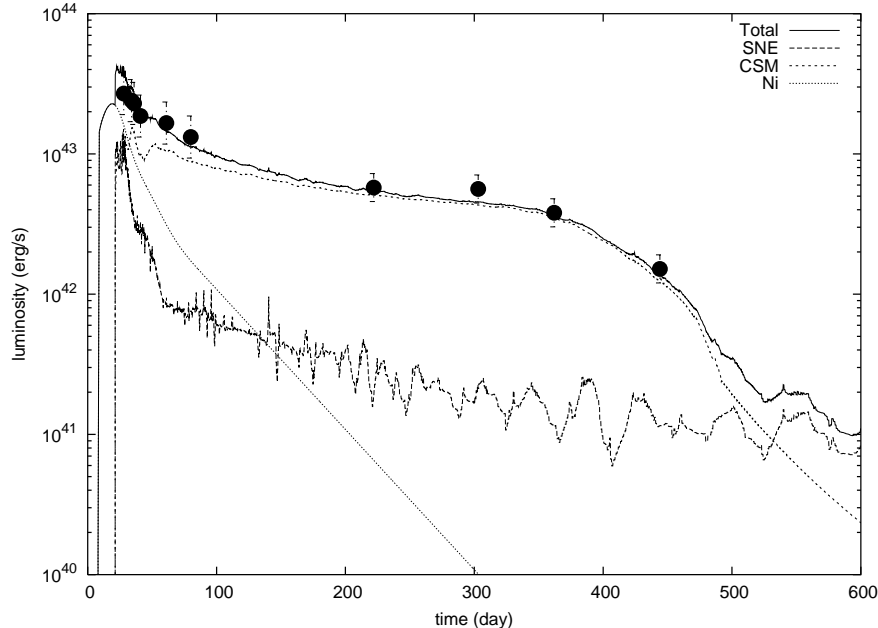
Figure 3. Calculated light curve with observed data points (filled circles: Deng et al. 2004).

Thielemann, & Yokoi 1984); its kinetic energy is $E = 1.3 \times 10^{51}$ erg. For CSM we assumed the power-law density distribution:

$$\rho = \rho_0 (r/R_0)^{-n} \text{g cm}^{-3} \tag{1}$$

where the parameters are the radius (R_0) and density (ρ_0) of the point where the ejecta and CSM start interacting, and the index (n) of the density distribution of CSM. These parameters are constrained from comparison with the observed light curve.

When the expanding ejecta interacts with CSM, the interaction creates the forward shock which is propagating through the CSM and the reverse shock which is propagating through the ejecta (propagating backwards in Lagrangian scheme).

Shocked matter is heated to $T \sim 10^7$ K for the reverse shock and $T \sim 10^9$ K for the forward shock. Both shocked regions emit thermal X-rays. For the reverse shock, because of relatively high densities in the ejecta, cooling time scale is shorter than shock propagation so that the shocked ejecta soon forms a dense cool shell (Suzuki & Nomoto 1995). This dense cool shell absorbs the X-ray and re-emits in UV-optical. This re-emitted photons are observed. We assume that a half of the X-rays emitted in the reverse-shocked ejecta is lost into the supernova center, and that the other half is transfered outwardly through the cooling shell. We also assume that a half of the X-rays emitted in the CSM is transfered inwardly to be absorbed by the cooling shell. We take into account
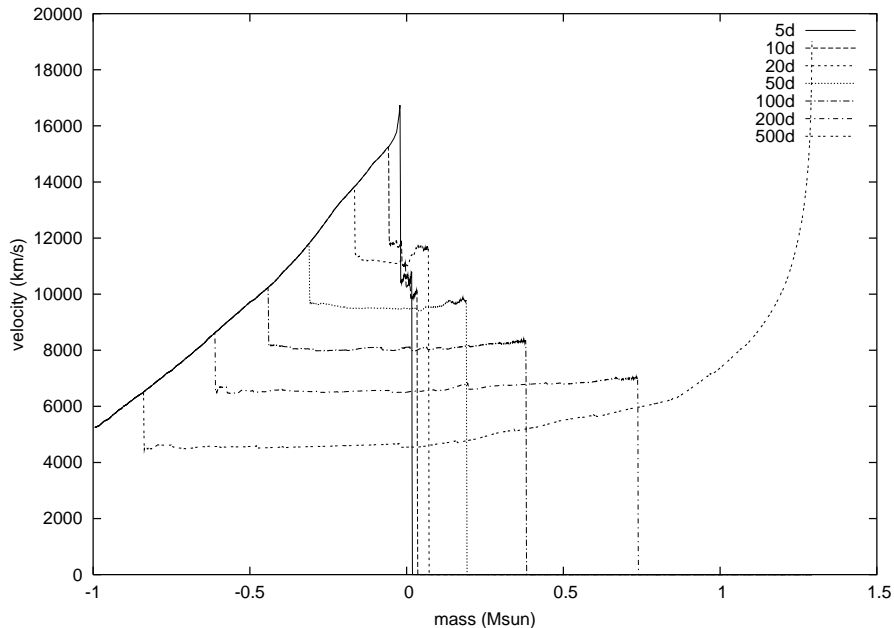
Figure 4.   Velocity profile in the interacting ejecta and CSM.

the change in time of the column density of the cooling shell to evaluate the X-rays absorbed by the shell and the optical luminosity.

Figure 3 shows the successful model for the light curve of SN 2002ic. The model light curve includes the radioactive decay using the bolometric light curve of SN 1991T. Recently, Wood-Vasey et al. (2004) reported the presence of a $\sim 1.7 \times 10^{15}$ cm gap from their analysis of the light curve. Therefore, we set $R_0 = 1.7 \times 10^{15}$ cm. For inner CSM of 1.1 $M_\odot$, $\rho_0 = 1.6 \times 10^{-15}$ g cm^{-3} and $n = 1.8$. For the wind velocity of $v_w = 10$ km s^{-1}, these parameters correspond to the mass-loss rate of $\dot{M} \sim 1 \times 10^{-3}$ $M_\odot$ yr^{-1}. In our initial model, the CSM is extend to 3.3×10^{16} cm, and this means that the super wind lasted for $\sim 10^3$ yr. In the early phase, the model with $n = 2.0$ (steady mass loss) declines too fast to be compatible with the observation. This implies that CSM around the SN was created by unsteady mass loss of the progenitor system.

After day ~ 350, the light curve starts declining. To reproduce the declining part of the light curve, we add the outer CSM of 0.2 $M_\odot$ where the density declines sharply as $n = 6$. This implies that the total mass of CSM is $\sim 1.3 M_\odot$.

The mass of CSM is much smaller than $\sim 4.7 M_\odot$ estimated in Nomoto et al. (2004), where we adopted solar chemical composition for the ejecta. As also reported in Chugai et al. (2004), a realistic chemical composition of the SN Ia ejecta results in more efficient cooling in the reverse shock and more efficient absorption of the X-rays in the supernova ejecta. These effects lead to the lower density and smaller total mass of CSM.

We note in Figure 4 that the velocity of the ejecta is $\lesssim 8,000$ km s^{-1} and too low for the observed broad component ($\geq 10,000$ km s^{-1}). In fact, in order

to produce high enough luminosity to explain the light curve, such a strong interaction between the ejecta and CSM should occur.

To reproduce both the light curve and the observed velocity of SN 2002ic, CSM needs to be aspherical. Suppose the CSM is aspherical consisting of a dense region and a thin region. The expanding ejecta interacting strongly with the dense region can produce high enough luminosity to explain the light curve. On the other hand, the ejecta interacting with the thin region can expand still fast enough to be consistent with the observed velocities.

5. Possible Progenitors of SN 2002ic

There are two possible progenitor scenarios for SN 2002ic. One is the explosion of the C+O core of the massive AGB star (SN I+1/2), where the wind from the AGB star formed the CSM. The other is the explosion of the white dwarf in a close binary blowing wind to create the dense CSM (e.g., Livio & Riess 2003; Chugai & Yungelson 2004).

5.1. Type I+1/2 Supernovae in AGB Stars

Single star scenario is the explosion of the massive AGB star whose C+O core becomes very close to the Chandrasekhar mass. Before explosion, mass loss (super-wind) from the star creates a dense CSM. The C+O core explodes, which is called Type I+1/2 supernova, and interacts with CSM.

To make this scenario possible, the metallicity of the system should be low because low mass loss rate is necessary for the C+O to grow to reach the Chandrasekhar mass before the envelope is completely lost. Under the solar metallicity, SN I+1/2 have never been observed. Therefore, we can explain the rarity of SN 2002ic-like event assuming that only narrow mass range of AGB stars can explode as SNe in low metal environment.

Aspherical CSM is not unexpected for stars approaching the end of the AGB. A pre-existing clumpy disk was also suggested by Wang et al. (2004), based on spectropolarimetry.

5.2. White Dwarf Winds

Binary star scenario is the explosion of the accreting C+O white dwarf (same as typical SNe Ia). However, the companion star is massive and the WD blows large amount of accreting gas as accretion wind to create the dense CSM. In this scenario, the rarity is can be attributed to the fewness of the companion star massive enough to produce the quite massive CSM.

As a progenitor of SN 2002ic, we need a CSM of $\sim 1.3\ M_\odot$. Such a massive CSM is possible only when the donor is as massive as $4 - 5 M_\odot$. For the model consisting of a WD and a main-sequence (MS) companion (Hachisu et al. 1999b), the mass transfer rate from such a massive MS companion reaches $\sim 1 \times 10^{-4} M_\odot\ \mathrm{yr}^{-1}$. Then the WD blows a wind of $\sim 1 \times 10^{-4} M_\odot\ \mathrm{yr}^{-1}$ and the mass stripping rate becomes several times larger than the WD wind mass loss rate (Hachisu & Kato 2003).

For the symbiotic model consisting of a white dwarf and a red giant or AGB star, the wind mass loss rate during the super-wind phase can also reach

$\sim 1 \times 10^{-4} M_\odot$ yr^{-1}. In symbiotic stars, the mass capture efficiency by the WD is observationally estimated to be as small as one or a few percent. Therefore, only when a large part of the red giant wind or AGB super-wind is captured by the white dwarf, the white dwarf can blow a very massive wind of $\sim 1 \times 10^{-5} M_\odot$ yr^{-1} or more. Then, the mass stripping rate from the red giant or AGB star also reaches several times $10^{-4} M_\odot$ yr^{-1} or more.

Examples of the accretion wind evolution are identified as transient super-soft X-ray sources, i.e., the LMC supersoft X-ray source RX J0513.9−6951 and its Galactic counterpart V Sge (Hachisu & Kato 2003). Especially in V Sge, a very massive wind of $\sim 1 \times 10^{-5} M_\odot$ yr^{-1} has been observationally suggested by the detection of radio. Furthermore, the white dwarf wind collides with the companion and strips heavily off its surface matter. This stripping rate reaches a few or several times the wind mass loss rate of the white dwarf, i.e., $\sim 1 \times 10^{-4} M_\odot$ yr^{-1} or more (Hachisu & Kato 2003). The matter stripped off has a much lower velocity than the white dwarf wind itself and forms an excretion disk around the binary. Thus the model predict the coexistence of a fast white dwarf wind blowing mainly in the pole direction and a massive disk or a torus around the binary. Deng et al. (2004) propose a new classification, Type IIa SNe, for these events.

6.   Rotation and Merging White Dwarfs

The issue of "single degenerate vs. double degenerates" has long been controversial. Nomoto & Iben (1985) and Saio & Nomoto (1998) have simulated the merging of double WDs in 1D and shown that the rapidly accreting WDs undergo off-center carbon ignition if $\dot{M} > 2 \times 10^{-6}\ M_\odot$ yr^{-1} because of compressional heating. Afterwards carbon flame propagates inward through the center and converts C+O into O+Ne+Mg. Then the final outcome is most likely accretion-induced collapse rather than SNe Ia.

Recently Piersanti et al. (2003a,b) calculated the evolution of WDs with rotation in 1D approximation. They assumed that all the angular momentum associated with the accreted matter was brought into the white dwarf. They claim that the combined effects of accretion and rotation induce expansion to make the surface zone gravitationally unbound and hence suppresses further accretion in the double white dwarf merger. They argued that the above effect makes the accretion rate smaller than the critical value for the occurrence of the off-center carbon ignition, and hence the white dwarf can grow up to the Chandrasekhar mass to become a SN Ia. However, they did not take into account the backward transport of angular momentum to the disk.

Saio & Nomoto (2004) have also calculated the accretion of C+O onto the C+O WD with rotation for various timescale of angular momentum transport in 1D approximation. The outermost layer of the accreting WD quickly reaches the critical rotation. Afterwards, the angular momentum is transported backward to disk and accretion continues (Paczyński 1991; Popham & Narayan 1991). For $\dot{M}$ > $3 \times 10^{-6}\ M_\odot$ yr^{-1}, off-center carbon burning is ignited prior to the central C-ignition. The difference in the total mass at the ignition between rotating and non-rotating models can be as large as $\sim 0.1 M_\odot$, depending on the assumed turbulent viscosity and the accretion rate. Thus the lifting effect of rotation

increases the critical accretion rate for the occurrence of off-center C-ignition by a factor of ~ 1.5 compared with the non-rotating case, but the basic conclusion is the same as non-rotating case, i.e., the accretion-induced collapse is the most likely outcome in the double degenerates scenario (Saio & Nomoto 1998).

For comparison, we note that Yoon & Langer (2004) also computed white dwarf models accreting CO-rich matter, taking into account the effect of rotation. The accretion rates they considered are lower than those adopted in the above calculations, thus leading to the C-ignition. They assumed that the matter accretes onto the white dwarf without bringing angular momentum when the rotation velocity at the surface of the white dwarf exceeds the Keplerian velocity. Under their assumption the total angular momentum of the white dwarf never decreases and is higher than Saio & Nomoto (2004) models for a given mass.

7. Surface Hydrogen Burning Models

For the single degenerate scenario, steady hydrogen-shell burning (Sienkiewicz 1975), which consumes hydrogen at the same rate as the white dwarf accretes, is a major evolutionary route to Type Ia supernovae (Nomoto 1982).

Recently, Starrfield et al. (2004) presented "*surface hydrogen burning models*" where steady and stable hydrogen burning occurs to increase the white dwarf mass to an SN Ia for the accretion rate in the range of $10^{-9} - 10^{-6} M_\odot$ yr^{-1}. This range is much wider than previous studies have found (Sienkiewics 1980).

Saio et al. (2004) have revisited the properties of white dwarfs accreting hydrogen-rich matter by constructing steady-state models and examining thermal stability of those models. Saio et al. (2004) have confirmed the results of Sienkiewicz (1975, 1980) and concluded that the steady "*surface hydrogen burning*" of Starrfield et al. (2004) is an artifact which arose from the lack of resolution for the envelope structure of their model.

In the surface zone (sz), the pressure at the burning shell is obtained as $P_{\rm sz} = GM\Delta M/4\pi R^4$, which is 9×10^{19} dyn cm^{-2} for $M = 1.35 M_\odot$, $R = 2400$ km, and $\Delta M = 1 \times 10^{-5} M_\odot$, where $10^{-5} M_\odot$ is the mesh size of their "*surface zone*" (Starrfield et al. 2004). Because of such a high pressure, the temperature in the surface zone is as high as $T_{\rm sz} \sim 5 \times 10^8$ K. When hydrogen-rich matter is accreted in the surface zone, $T_{\rm sz}$ is high enough to burn hydrogen and helium immediately, and the nuclear energy generation rate is determined by the mass accretion rate. Such a "steady" burning is just due to the too coarse mesh size of their surface zone.

Actual hydrogen-burning occurs in such a superficial layer as $\sim 10^{-7} M_\odot$. Then "surface" hydrogen burning should be unstable to flash for $\dot{M} < 10^{-7} M_\odot$ yr^{-1} (Sienkiewicz 1980; Saio et al. 2004).

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